

3D ACOUSTIC SIMULATIONS FOR NONLINEAR ACOUSTIC CONCEALED WEAPONS DETECTION

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Abstract

Detecting concealed weapons and explosives on persons is an important and challenging problem. We have developed a device that uses sound waves to detect concealed weapons and explosives at large standoff distances. Computer simulations are used to understand the complicated physics of nonlinear acoustic propagation and acoustic scattering. These simulations are used to design optimal hardware devices and to test signal processing algorithms. An overview of acoustic concealed weapons detection and the two computer simulation methods we developed will be presented.

Introduction

Current weapon detection technologies are often inadequate because they only detect metal objects at short distances. Our post 9/11 studies in acoustic concealed weapons detection are showing great potential in their ability to detect concealed objects at significant stand-off distances¹. The development of acoustic weapons detection technology will require exhaustive experiments, full 3D and nonlinear acoustic computer simulations, and sophisticated signal processing algorithms.

An acoustic weapons detection system consists of an ultrasonic transducer that emits a short inaudible acoustic pulse into the air. This sound propagates away from the transducer until it comes in contact with the target person. The sound waves interact with the person's clothing, body, and any objects in-between. Some of the acoustic energy reflects back to the transducer where it is recorded on a computer as a waveform. The structure of the waveform depends on the details of the interaction of the sound waves with the person. A waveform from a person with a concealed weapon will differ from a waveform from a person without a concealed weapon. One of the goals of this project is to develop artificial intelligence

Narrow frequency band transducers are typically used to create the initial sound burst in acoustic concealed weapons detection². Using parametric arrays to create the initial sound burst may have many advantages over typical transducers. Parametric arrays emit high

powered ultrasound waves that transition to lower frequencies waves because of the nonlinear and absorption effects in air. These effects allow for the creation of a low frequency and narrow sound beams that can deliver acoustic energy over large distances. Traditional air-coupled transducers have very narrow frequency bands that only allow for single frequency tone-bursts. In contrast, parametric arrays have a broad frequency band that allows the initial waveform to contain a range of frequencies. Also, the lower frequencies produced by the parametric array will penetrate clothing more effectively than the higher ultrasound frequencies.

The photograph in figure 1 shows the current experimental apparatus for nonlinear concealed weapons and explosives detection. A Sennheiser Audio Beam parametric array (left of picture) is used to create a narrow sound beam. A parabolic microphone is used to receive any returning acoustic waves. The waveforms are digitized and analyzed on a standard laptop computer.

The physics of the nonlinear acoustic propagation and the acoustic scattering from the person is a very complicated. We have developed computer simulation techniques to better understand both stages of the nonlinear concealed weapons process. We use a finite



Figure 1. Picture showing the experimental nonlinear acoustic concealed weapons and explosives detection apparatus.

difference technique to simulate the nonlinear acoustic wave propagation from the parametric array to the person based on the KZK nonlinear acoustic wave equation. Then, we use a full 3D finite integration simulation to model the sound wave interaction with the person, clothing layers, and any concealed objects. With these two simulation methods, we can simulate the entire physical process to design optimal hardware configurations and develop signal processing techniques.

KZK Nonlinear Acoustic Simulations

To model nonlinear acoustic beams, we turn to numerical solutions of the Khokhlov-Zabolotskaya-Kuznetsov (KZK) equation. The KZK equation is a nonlinear parabolic wave equation that accounts for the combined effects of diffraction, absorption, and nonlinearity in finite amplitude acoustic beams. In the derivation of the KZK equation, the sound waves are assumed to form a directive beam that permits a parabolic approximation to be made in the term that accounts for diffraction. The parabolic approximation introduces errors at more than 20° off the beam axis and at locations close the source³. For concealed weapons detection, we are only interested in the sound waves near the beam axis and far from the parametric array. So, numerical solutions of the KZK equation work well for modeling parametric array emissions for concealed weapons detection.

The KZK equation (Equation 1) for an axis-symmetric sound beam that propagates in the positive z-direction can be written in terms of the acoustical pressure p . The first term on the right-hand side accounts for diffraction, the second term accounts for absorption, and the third accounts for nonlinearity. Lee and Hamilton developed a finite difference method for simulating nonlinear sound beams based on the KZK Equation . We developed a simulation code to model parametric arrays for use in concealed weapons detection based on Lee and Hamilton's method.

Figure 2 shows several time snapshots of a short dual-tone ultrasonic pulse (45 and 55 kHz) from a focused 2ft diameter parametric array. This figure shows the pressure wave propagation from both a nonlinear (top) and linear (bottom) simulation. As the pulse propagates away from the parametric array, the sound waves

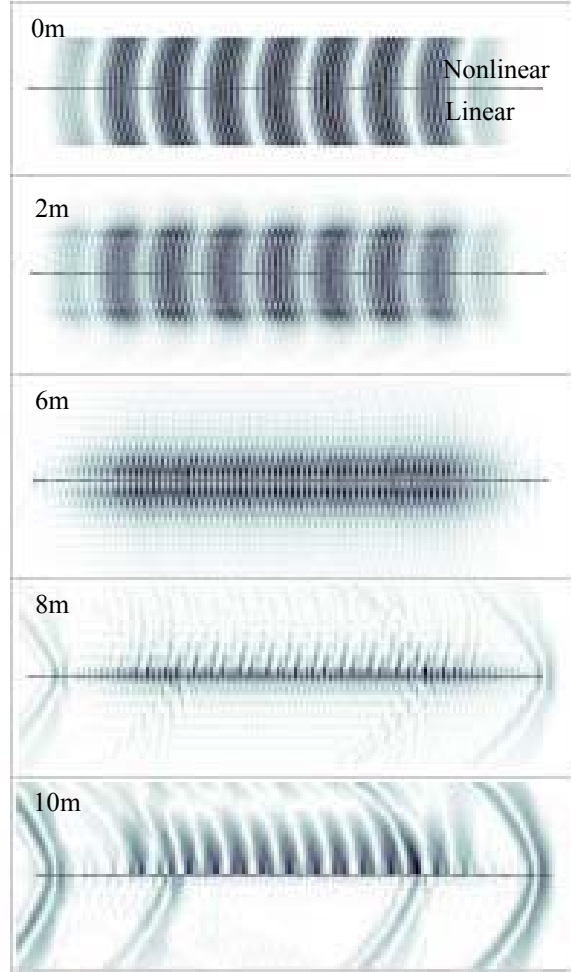


Figure 2. Simulated acoustic pulse propagation from a parametric array. Each figure is split showing a nonlinear simulation on the top and a linear simulation on the bottom. The initial wave is a dual tone burst (45kHz and 55kHz). At 8m, a 10kHz difference frequency is clearly shown only in the nonlinear simulation.

become focused and the high frequency waves start to drop in intensity because of absorption. In the nonlinear simulation, one can clearly see the emergence of a 10 kHz waveform. This 10kHz component is due to the self-demodulation of the original pressure waveform because of the nonlinearity in air. This is how parametric arrays create low frequency and narrow sound beams.

With the KZK nonlinear acoustic simulations, we can

$$\frac{\partial^2 p}{\partial z \partial t'} = \frac{c_0}{2} \left(\frac{\partial^2 p}{\partial r^2} + \frac{1}{r} \frac{\partial p}{\partial r} \right) + \frac{D}{2c_0^3} \frac{\partial^3 p}{\partial t'^3} + \frac{\beta}{2\rho_0 c_0^3} \frac{\partial^2 p^2}{\partial t'^2} \quad (1)$$

test different parametric array specifications to judge their effectiveness for concealed weapons detection. For example, we can change the parametric array size, curvature (for focusing), frequency, and initial intensity. We can also test environmental effects such as air temperature and humidity level to study how these variables effect the acoustic wave propagation. We have successfully used these KZK nonlinear simulations to provide design guidelines for custom parametric arrays and to accurately predict the sound waveforms they produce.

3D Acoustic Finite Integration Technique

The KZK simulations allow us to model the pressure waveforms produced by a parametric array and propagate them over long distances. But, these KZK simulations do not allow us to simulate the acoustic interaction of the sound waves with the person. To model the acoustic interaction with a person, clothing layers, and any concealed objects, we need to use a full 3D acoustic simulation method.

We have developed a 3D acoustic simulation method using the finite integration technique. The finite integration technique is a powerful, accurate, and stable time-domain method for numerically solving partial differential equations. It has been used successfully to model 2D, axial-symmetric (2.5D), and full 3D acoustic and elastic waves in the Cartesian and Cylindrical coordinate systems⁴⁻⁵. We begin with the basic acoustic equations (Equations 2-3) that relate the pressure and velocity components of a fluid⁶.

$$\frac{\partial p}{\partial t} + \rho_0 c_0^2 \nabla \cdot \vec{v} = M \quad (2)$$

$$\rho_0 \frac{\partial \vec{v}}{\partial t} + \nabla p = \vec{F} \quad (3)$$

We transform these partial difference equations using the Finite Integration Technique to reveal equations 4-7. The pressure p and velocity v values are distributed on a staggered grid. The material parameters c_0 and ρ_0

$$p^{t+\Delta t/2} = p^{t-\Delta t/2} - \frac{\rho_0 c_0^2 \Delta t}{\Delta x} \left((v_1^{1+} - v_1^{1-}) + (v_2^{2+} - v_2^{2-}) + (v_3^{3+} - v_3^{3-}) \right) + M \Delta t \quad (4)$$

$$v_1^t = v_1^{t-\Delta t} - \frac{\Delta t}{\rho_0 \Delta x} (p^{1+} - p^{1-}) + \frac{\Delta t F_1}{\rho_0} \quad (5)$$

$$v_2^t = v_2^{t-\Delta t} - \frac{\Delta t}{\rho_0 \Delta x} (p^{2+} - p^{2-}) + \frac{\Delta t F_2}{\rho_0} \quad (6)$$

$$v_3^t = v_3^{t-\Delta t} - \frac{\Delta t}{\rho_0 \Delta x} (p^{3+} - p^{3-}) + \frac{\Delta t F_3}{\rho_0} \quad (7)$$

are also discretized and spatially aligned with the pressure values. This places the velocity values on the boundary between any two materials. These difference equations enforce that the normal of material displacement is continuous across any material boundary. With these difference equations and the appropriate boundary and stability criteria, we can simulate acoustic interactions with objects and collections of objects of any material type.

Parallel Implementation

For concealed weapons detection, we need to model large and complex scenarios. This requires a substantial amount of computer resources. For example, a 2 meter cube computational space with a resolution of 2 millimeters requires one billion cell volumes. A computational space of this size would require 48 Gigabytes of computer memory. This amount of computer memory is not available even on high-end desktop computers. To overcome this high computational demand, we have implemented the 3DAFIT code to run on a parallel computer⁷. This is done by dividing the computational space up between many computers. In between time steps, each computer swaps boundary values with neighboring computers to create a large and seamless simulation space. Running simulations on a parallel computer drastically lowers the time it takes to run simulations. For example, a medium sized simulation with 27 million nodes (such as the ones shown in figure 3) takes approximately 10 minutes running across 30 one GHz processor machines.

Acoustic Scattering from Simple Objects and Material Layers

Objects can be placed into the simulation space to study how the acoustic waves interact with them. Figure 3 shows a 10 kHz plane wave scattering from a sphere (left) and three cylinders (middle). In these two cases, the objects are rigid; meaning the material velocity at the boundary is zero. The scattered acoustic wave looks as one would expect from these simple objects.

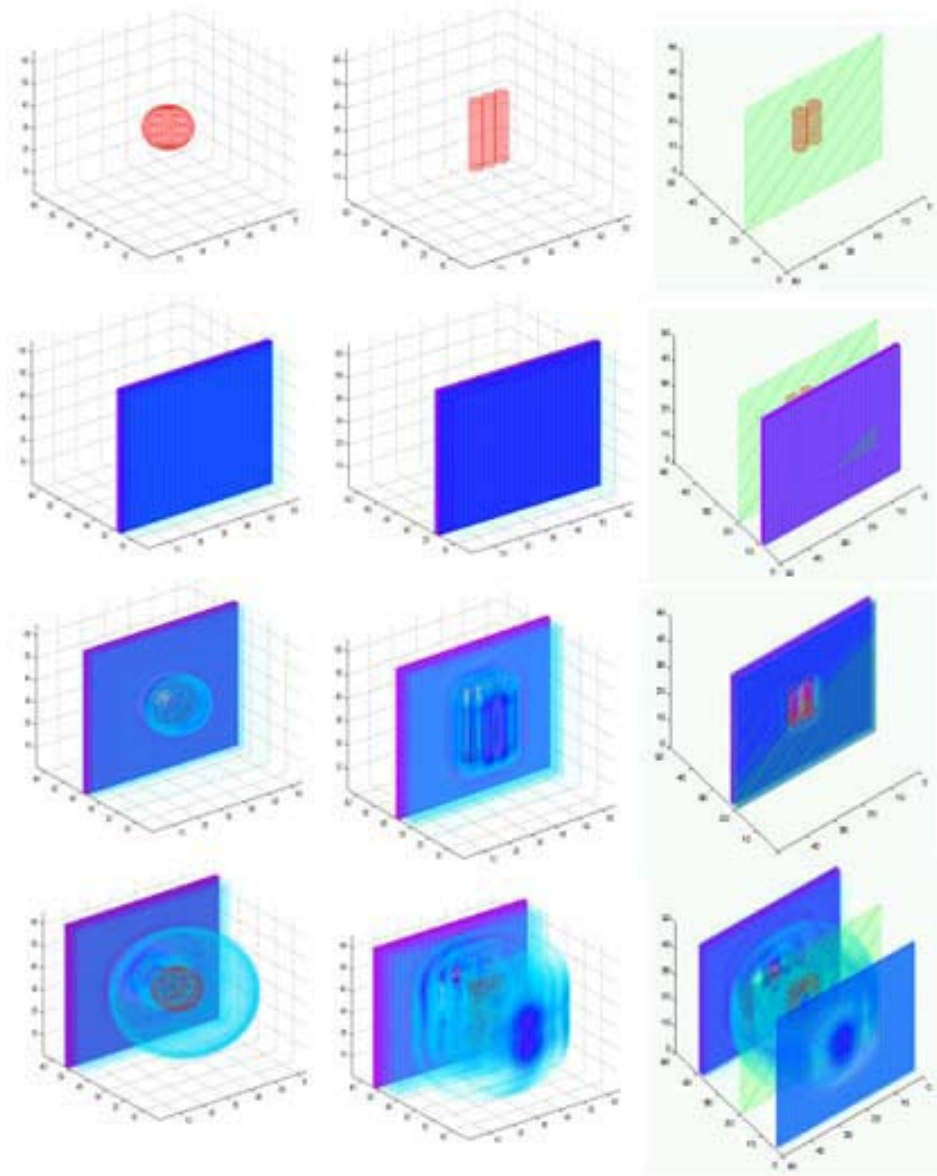


Figure 3. 3D acoustic scattering simulation snapshots of a 10 kHz plane wave scattering from a sphere (left), three cylinders (middle), and two cylinders behind a thin layer that reflects 25% of the acoustic energy (right).

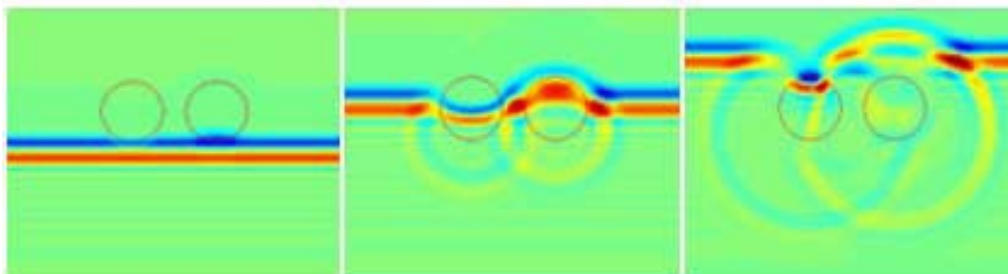


Figure 4. 2D pressure snapshots from a 3D acoustic simulation. Two cylinders of different material compositions are placed in the middle of the simulation space. A 10 kHz acoustic wave passes through the two cylinders differently because of the difference in material composition.

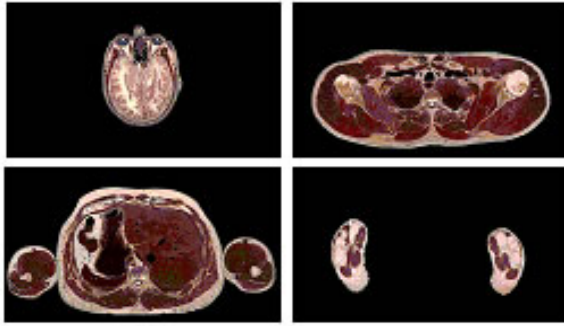


Figure 5. Anatomical cross-sections taken from a male cadaver obtained by the Visible Human Project.

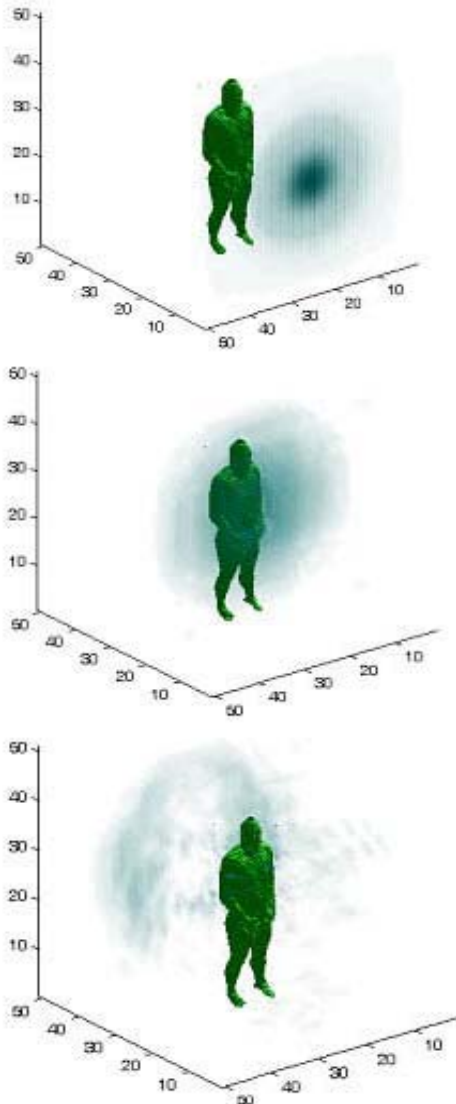


Figure 6. An acoustic pulse from the KZK simulation shown in figure 3 scatters from the 3D human model.

Objects of different material properties can be placed into the simulation space. The right column of figure 3 shows a 10kHz plane wave scattering from two rigid cylinders placed behind a thin material layer. The thickness and properties of these layers can be adjusted to mimic specific types of clothing. In this case, the layer allows 75% of the acoustic energy to penetrate. The scattered acoustic wave from the two cylinders is obstructed by the scattered wave of the layer. This demonstrates how clothing layers will complicate the interpretation of the backscattered acoustic waves. Figure 4 shows a 2D slice through a 3D simulation of a 10kHz plane wave interacting with two cylinders of different material parameters. The sound waves travel at different speeds through the cylinders. This creates two different backscattered waves.

Acoustic Scattering from 3D human Model

To create the most realistic scenarios, we have included a 3D human model into our acoustic scattering simulations. The 3D human model was created from low resolution anatomical cross-sections taken from a male cadaver obtained by the Visible Human Project⁸. Figure 5 shows four sample anatomical cross-sections from this dataset. We are currently working on a higher resolution model from high resolution images from the Visible Human Project. With the higher resolution images, we will be able to create more accurate models of both a male and female body.

We have successfully merged our KZK simulation code and our 3D acoustic finite integration (3DAFIT) code. The KZK simulation code is used to propagate the acoustic wave from the parametric array to the target taking into account the effects of nonlinearity and absorption. At a certain distance, the pressure waves flow from the KZK simulation space into the 3DAFIT simulation space. We can place any combination of objects and layers into the 3DAFIT simulation space to study the acoustic interaction.

Figure 6 shows a full 3D acoustic scattering from the human model. The incoming waves are from a KZK simulation. A one meter diameter focused parametric array emits a short dual-tone pulse (45 kHz and 55 kHz). As the pulse propagates away from the parametric array, a 10 kHz component is created due to the nonlinearity of the air. At 10 meters, only the 10 kHz component of the pulse remains because the higher ultrasound frequencies were absorbed much more quickly than the 10 kHz component. This waveform then propagates into the 3DAFIT simulation space where it scatters from the 3D human model.



Figure 7. A 3D model of the RPG-7V1 Rocket Propelled Grenade Launcher is shown at three angles in the ca

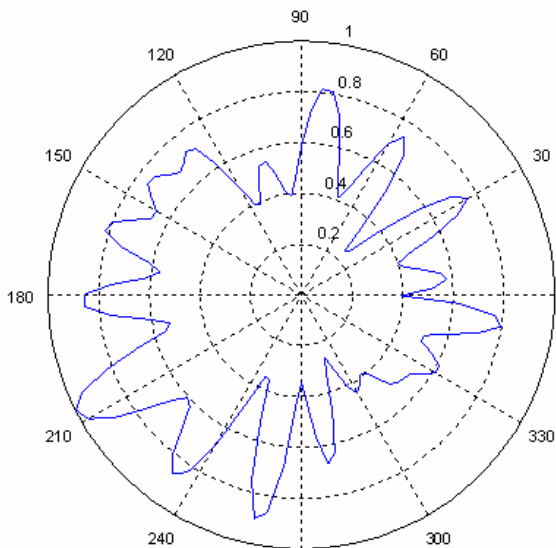


Figure 8. Polar plot shows the backscattered energy of the RPG-7V1 model as a function of incident wave angle.

Acoustic Scattering from Weapons

In addition to acoustic scattering from a human model, it is important to accurately model weapons and explosives. Figure 7 shows a 3D model of a RPG-7V1 Rocket Propelled Grenade Launcher. The dimensions of each of the major geometrical features of the RPG were extrapolated from an RPG image. The 3D model was created in a commercial CAD package and imported and rendered in the MATLAB environment. Once in the MATLAB environment, we can position it

into our simulation space at any orientation to study how acoustic waves interact with it.

Figure 8 shows the acoustic backscatter as a function of angle at 6kHz. The peak and valley structure of the backscattered energy is as expected and is the most interesting part of the data. In some cases, a small change in orientation (as small as 10°) can lead to a 60% drop in the backscattered energy. But, this plot only shows the backscattered energy at 6 kHz. A collection of these backscattered-energy vs. angle plots at different frequencies can provide a template of what to look for in experimental measurements. Knowing how acoustic waves reflect from a complicated shaped weapon is necessary to develop a successful signal processing algorithms to automatically detect them.

Experimental Verification

To verify the combined KZK and 3DAFIT simulation method, a systematic experimental study along with complementary scattering simulations were performed⁹. The experimental apparatus, pictured in figure 1, is composed of a commercial parametric array (Sennheiser's AudioBeam), a parabolic microphone, and a laptop computer. In this particular experiment the excitation waveform is a linear frequency modulated chirp starting at 500Hz, ending at 9400 Hz, and 0.4 seconds long. In air, the acoustic wavelengths of this chirp range from 66cm at 500Hz to 3.5 cm at 9400 Hz. This broad range of acoustic wavelengths is designed to provide a lot of useful information about the scatterer. The sound waves interact with the two 18 inch long PVC pipes suspended 15 feet away from the experimental apparatus. The cylinders have a two inch inner diameter and are rotated in 5 degree increments while pulse-echo measurements are taken. A top-down view of the cylinders and the incident sound beam

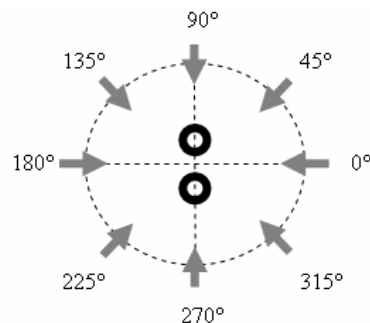


Figure 9. Top-down view of the two PVC pipes with the angles of the incoming sound beam shown.

angle is shown in figure 9.

Systematic simulations were performed to compare to the experimental data with a KZK simulation used to propagate a sound pulse approximately 13 feet. Then the sound waves flowed into the 3D acoustic simulation space where they scattered from the two cylinders as they were rotated in 9 degree increments. Figure 10 shows a polar plot of the acoustic backscattered energy at 4 kHz as a function of incident sound angle for both simulated (black) and at 4.2 kHz for the experimental (gray) measurements. The lobe structure of these two plots is very similar and the small error between the two plots is within the variation of the experimental measurements. The similarities between experimental and simulated measurements give us confidence that the combined simulation method accurately captures the relevant physics for our application.

Conclusions

We have successfully developed a simulation code to accurately model nonlinear acoustic wave propagation from parametric arrays based on the nonlinear KZK wave equation. With this model, we can systematically test different parametric array configurations to determine the best design parameters for a given weapons detection situation. We have also developed a parallel 3D acoustic scattering simulation method for modeling acoustic wave interactions with humans, clothing layers, and objects. With this model, we can systematically explore acoustic wave interactions with various objects at different angles. We have combined these two simulation methods to provide insight to developing signal processing algorithms to detect concealed weapons and explosives. Results from the combined simulation method show good agreement with experimental results.

References

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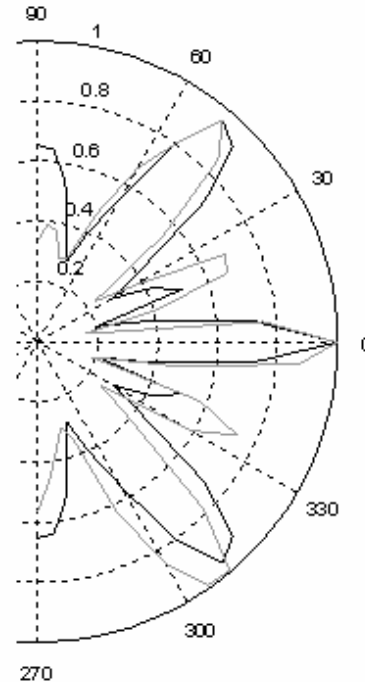


Figure 10. Polar plot showing the acoustic backscattered energy as a function angle at 4.2kHz. Black represents the simulation results and gray represents the experimental results.

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